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Dosimetric Comparison of Halcyon vs. TrueBeam Equipment and VMAT vs. Hybrid-IMRT Techniques in Radiotherapy for Bilateral Breast Cancer Treatment

QIU XiBin[1], Mak KengLok[1], Mak KinLong[2], Yeung HoWai[2], Ho NokHang[2], Lo HoTing[2], Kwok KaSan[2] and CHAU MingChun[1,2*]

[1]*Department of Oncology, Kiang Wu Hospital, Macau.*

[2]*Medical Science and Health, Tung Wah college, Hongkong.*

***Correspondence:**
CHAU MingChun, Department of Oncology, Kiang Wu Hospital, 19/F, MHS of Tung Wah College, 31 Wylie Road, Homantin, Kowloon, Hong Kong, Phone: +852 91960094.

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ABSTRACT

Objective: *The present investigation intends to identify the optimal radiotherapy treatment for synchronous bilateral breast cancer (SBBC) using two RT equipment with two planning techniques.*

Methods: *A retrospective analysis was conducted on ten consecutive SBBC patients treated at Oncology center of Kiang Wu Hospital. Dosimetric parameters of target volumes and normal tissues were compared across different equipment (Halcyon, TrueBeam) and techniques (VMAT, Hybrid-IMRT). Compliance with RTOG1005 dosimetric constraints was evaluated and statistical differences between techniques were analyzed.*

Results: *VMAT-Halcyon (VMAT-Hal) demonstrated significantly better target Conformity Index (CI) than Hybrid-IMRT (P=0.02), with no significant difference in Homogeneity Index (HI). Compared to Hybrid-IMRT, VMAT-Hal reduced lung doses, particularly in high-dose regions. VMAT-Hal lowered cardiac V5 (15% vs. 22%, P=0.03) and left anterior descending artery (LAD) dose (10 Gy vs. 14 Gy). Beam-on time with Halcyon was 29% shorter than TrueBeam (2.42 min vs. 3.41 min).*

Conclusion: *VMAT-Halcyon is the preferred treatment modality that balancing target coverage, normal tissue sparing and treatment efficiency.*

Keywords

Bilateral breast cancer, Radiotherapy, Halcyon, TrueBeam, VMAT, Hybrid-IMRT.

Abbreviations

BBC: bilateral breast cancer, RT: Radiation Therapy, CI: Conformity index, FFF: Flattening filter-free, HI: Homogeneity index, IMRT: Intensity modulated radiation therapy, LAD: Left anterior descending artery, MBBC: Metachronous bilateral breast cancer, MLC: Multi-leaf collimator, Mu: Monitor unit, OAR: Organ at risk, RTOG: Radiation Therapy Oncology Group, SBBC: Synchronous bilateral breast cancer, VMAT: Volumetric modulated arc therapy, Vx: Percentage volume receiving a dose of X Gy.

Introduction

Bilateral breast cancer (BBC) is defined as breast cancer diagnosed simultaneously or within a short interval in both breasts [1]. It is considered to result from the combined effects of shared genetic predisposition and acquired adverse factors, representing dual primary lesions rather than metastatic disease [2]. Reported incidence rates of BBC range from approximately 3% to 5% [3].

Radiotherapy planning for BBC is more challenging than for

unilateral breast cancer. BBC is not an independent poor prognostic factor. Most breast cancer patients can achieve long-term survival, it is essential to minimize long-term radiation-induced side effects. Currently, there are no specific radiotherapy guidelines tailored for BBC. Bilateral irradiation doubles the treatment volume and creates irregular shapes, yet the dose tolerance limits for normal tissues (such as heart and lungs) must still adhere to the standards established for unilateral breast cancer radiotherapy. The positioning for bilateral tumor bed irradiation is more complex and time-consuming. Therefore, it is necessary to ensure patient comfort and maintain treatment precision.

When designing radiotherapy plans, it is necessary to select the equipment (O-ring linear accelerator or C-arm linear accelerator) and techniques (VMAT or Hybrid-IMRT). In busy clinical practice, it is difficult to perform separate plan designs using different equipment and techniques for each patient, and the results of individual cases may lack representativeness. Radiotherapy for BBC is uncommon, making it challenging to accumulate planning experience continuously. Therefore, the Oncology Department of Kiang Wu Hospital collaborated with Hong Kong Tung Wah College to perform a study in selection of ten cases of BBC patients treated in Kiang Wu hospital in recent years. Radiotherapy plans were designed with VMAT and Hybrid-IMRT techniques using Halcyon and TrueBeam equipment to compare the dosimetric differences in target coverage and normal tissue sparing among different equipment and techniques, providing a reference for clinical decision-making.

Methods

Patient Selection

Ten SBBC patients without axillary nodes involvement consecutively treated at the Oncology Department of Kiang Wu Hospital from 2015 to 2022 were selected in this retrospective study. Exclusion criteria included non-simultaneous bilateral radiotherapy, distant metastases, history of chest radiotherapy and patients who underwent breast reconstruction surgery.

Planning Objectives

For each patient, CT-simulation scans were acquired with a thickness of 2.5mm in free breathing mode. Treatment plans were designed using VMAT-Hal, VMAT-TB and Hybrid-IMRT techniques, with target volumes and normal tissues contoured by the same oncology physician according to the RTOG 1005 protocol [4]. Normal tissues included the lungs, heart, LAD, liver and skin. The treatment planning system was Varian Eclipse v15, using the Analytical Anisotropic Algorithm for dose calculation. Ten patients were planned with VMAT-Hal, VMAT-TB, and Hybrid-IMRT techniques and a total of 30 plans were created for comparison. For VMAT planning, the isocenter was placed at the posterior edge of the sternum in the midline, using a four-arc design: two counterclockwise arcs from 150° to 210° and two clockwise arcs from 210° to 150°. For Hybrid-IMRT planning, two isocenters were located separately in the center of the left and right PTVs. Eighty percent of the dose was delivered via tangential fields, with field angles adjusted based on the medial and lateral borders of the bilateral targets to avoid overlapping at the midline. Twenty percent of the dose was delivered via IMRT fields, with four IMRT fields incident at angles of ±10° to 20° relative to the tangential fields.

Evaluation Parameters

1. Target coverage metrics: Target volume D100, D98, D2 doses; V107 and V10 volumes; conformity index (CI) and homogeneity index (HI).
2. Normal tissue protection metrics: Mean doses to lungs, heart, LAD, liver and skin; irradiated volumes receiving 5Gy to 40Gy doses.
3. Radiotherapy delivery: beam-on time.

Statistical Analysis

The data were analyzed using SPSS v23.0. Since the data in this study was not normally distributed and had outliers in the Hybrid-IMRT plans, the Wilcoxon signed-rank test was employed to compare the dose parameters mentioned above. This test evaluated the statistical significance of differences between VMAT-Hal vs. VMAT-TB, VMAT-Hal vs. Hybrid-IMRT and VMAT-TB vs. Hybrid-IMRT. A p-value < 0.05 was considered statistically significant.

Results

1. The description of clinical characters of the ten patients were listed in Table 1.
2. Three plans (VMAT-Hal, VMAT-TB, and H-IMRT) were designed for each patient and a total of 30 plans were created. The average values and standard deviations of D100, D98, D2 doses, V107 and V10 volumes for bilateral PTV, along with CI, HI and corresponding p-values were shown in Table 2. Bold italics data indicated those parameters that failed to meet RTOG 1005 requirements, while bold data represented those parameters with p-value <0.05. The results demonstrated that VMAT techniques provide superior target conformity and homogeneity compared to Hybrid-IMRT technique. However, no significant differences were observed between VMAT-Hal and VMAT-TB techniques.
3. The Hybrid-IMRT planning approach resulted in unoptimizable dose hotspots exceeding tolerance limits at the midline overlapped region in three patients due to the close distance of bilateral target volumes, as illustrated in Figure 1.
4. The mean values, standard deviations, and p-values of different dose-volume parameters for normal tissues (bilateral lungs, heart, LAD, liver, and skin) were shown in Table 3. Bold italics data indicated those parameters that failed to meet RTOG 1005 requirements, while bold data denoted p-value <0.05.
5. Beam-on time comparison for the 30 plans were presented in Table 4. Note that RTOG 1005 does not specify the requirements for beam-on time. Bold data indicated a p-value <0.05.

Table 1: Clinical characteristics of selected ten patients.

Character	Classification / Number	Number
Age	Median (Range)	52 (38-67)
Pathology	Bilateral same	6
	Bilateral different	4
	Bilateral invasive tumor	8
	One side Invasive tumor, one side Tis	2
T	Tis	2
	T1	5
	T2	1
	T3	2
N	N0	10
Surgery	Bilateral BCT	2
	One side BCT, one side mastectomy	6
	Bilateral mastectomy	2
RT fields	Bilateral breast	2
	One side breast, one side chest wall	6
	Bilateral chest wall	2
MRI examination	Arranged	1
	Not arranged	9
Gene test	Arranged	1
	Not arranged	9

Table 2: Comparison of Target Dose Parameters among VMAT-Hal, VMAT-TB and H-IMRT

Target	Parameters	VMAT-Hal (Mean±SD)	VMAT-TB (Mean±SD)	H-IMRT (Mean±SD)	VMAT-Hal vs VMAT-TB (p)	VMAT-Hal vs H-IMRT (p)	VMAT-TB vs H-IMRT (p)
Right PTV	D100	97.0 ±1.33	96.8 ±0.95	95.4 ±0.77	0.45	**0.02**	**0.005**
	D98	39.8 ±0.34	39.7 ±0.26	38.8 ±1.18	0.39	**0.02**	**0.005**
	D2	42.9 ±0.08	42.8 ±0.13	43.2 ±0.94	0.11	0.65	0.333
	V107	2.2 ±0.87	1.5 ±0.79	***12.5 ± 22.50***	0.17	0.45	0.333
	V110	0.003 ±0.005	0.01 ±0.01	***2.6 ±6.34***	0.06	0.40	0.721
Left PTV	D100	97.0 ±1.44	96.9 ±1.43	95.5 ±0.52	0.80	**0.01**	**0.005**
	D98	39.8 ±0.38	39.8 ±0.38	38.8 ±1.64	0.96	**0.005**	**0.007**
	D2	42.8 ±0.18	42.8 ±0.12	43.3 ±0.79	0.51	0.07	0.093
	V107	2.2±1.10	1.8 ±0.85	***8.8 ±16.60***	0.39	0.07	0.017
	V110	0.01±0.01	0.01 ±0.01	***2.9 ±7.58***	0.31	0.24	0.26
Right PTV	HI	0.08±0.009	0.08±0.01	0.11±0.06	0.72	0.05	0.047
Left PTV	HI	0.08±0.009	0.08±0.008	0.11±0.05	0.88	0.005	0.007
Bilateral PTV	CI	0.9 ±0.03	0.9 ±0.03	0.72 ±0.14	0.11	0.007	0.007

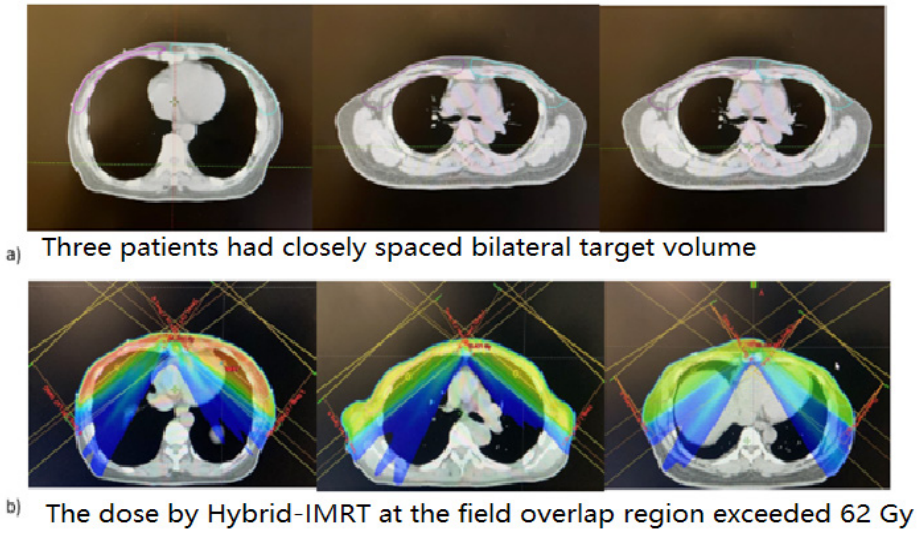

Figure 1: Target volumes dose distributions of Hybrid-IMRT for three representative patients.

Table 3: OAR comparison among VMAT-Hal, VMAT-TB and H-IMRT

OAR	parameters	VMAT-Hal (Mean±SD)	VMAT-TB (Mean±SD)	H-IMRT (Mean±SD)	VMAT-Hal vs VMAT-TB (p)	VMAT-Hal vs H-IMRT (p)	VMAT-TB vs H-IMRT (p)
Heart	V40	0.0003 ± 0.0008	0.007 ± 0.02	***0.69 ± 1.11***	0.18	**0.04**	0.17
	V30	0.29 ± 0.27	0.22 ± 0.32	***2.50 ± 2.93***	0.40	**0.02**	**0.02**
	V20	1.49 ± 1.15	1.21 ± 0.87	***5.43 ± 7.63***	0.39	**0.03**	**0.02**
	V10	6.48 ± 2.41	6.52 ± 1.91	***14.22 ± 13.73***	0.88	0.07	0.39
	V5	21.01 ± 3.98	28.58 ± 7.77	25.03 ± 19.28	0.07	0.58	0.20
	Dmean	4.26 ± 0.58	5.02 ± 0.26	5.12 ± 3.31	**0.005**	0.72	0.88
Llung	V40	0.057 ± 0.09	0.09 ± 0.16	1.79 ± 2.71	0.72	**0.02**	**0.04**
	V30	5.36 ± 1.46	5.08 ± 1.74	***10.89 ± 5.61***	0.45	**0.007**	**0.005**
	V20	12.18 ± 1.65	12.28 ± 1.88	***15.77 ± 6.43***	0.88	0.11	0.07
	V10	23.17 ± 0.57	***25.08 ± 2.13***	***29.76 ± 13.41***	**0.007**	0.06	0.29
	V5	45.0 ± 11.51	***64.69 ± 13.67***	44.21 ± 13.79	**0.05**	0.72	**0.03**
R lung	V40	0.029 ± 0.046	0.08 ± 0.12	2.01 ± 2.53	0.17	**0.01**	**0.01**
	V30	4.24 ± 2.51	4.46 ± 2.43	***11.16 ± 7.65***	0.88	**0.005**	**0.005**
	V20	10.29 ± 4.04	11.52 ± 3.01	***16.49 ± 10.13***	0.14	**0.01**	0.06
	V10	22.44 ± 1.50	***25.10 ± 2.88***	***34.71 ± 16.88***	**0.02**	**0.03**	**0.05**
	V5	48.30 ± 8.82	***66.11 ± 14.38***	53.03 ± 19.84	**0.007**	0.45	0.14
LAD	V40	0 ± 0	0.11 ± 0.35	***8.08± 14.74***	0.32	0.07	0.14
	V30	4.07 ± 7.13	2.91 ± 7.61	***31.49 ± 22.58***	0.75	**0.008**	**0.008**
	V20	18.93 ± 13.26	15.21 ± 15.25	42.56 ± 26.66	0.33	0.14	0.007
	V10	45.49 ± 10.58	40.63 ± 11.69	***66.30 ± 18.25***	0.72	**0.005**	**0.01**
	V5	63.29 ± 8.95	70.74 ± 9.07	79.07 ± 14.68	**0.047**	**0.005**	0.11
	Dmean	11.27 ± 2.60	10.64 ± 3.60	***19.28 ± 7.56***	0.39	**0.02**	**0.009**
	Dmax	30.20 ± 6.55	28.83 ± 6.87	37.47± 5.81	0.45	**0.005**	**0.01**
Liver	Dmean	4.26 ± 1.25	4.74 ± 1.30	3.34 ± 2.26	0.39	0.11	0.07
Skin	V40	1.68 ± 0.93	2.11 ± 0.78	2.47 ± 0.98	0.24	0.09	0.65
	V30	23.15 ± 5.71	22.90 ± 4.87	23.45 ± 4.76	0.88	0.72	0.51
	Dmean	16.47 ± 4.88	15.70 ± 1.84	14.99 ± 2.18	0.11	0.51	0.11

Table 4: Bean-on time comparison among VMAT-Hal, VMAT-TB and H-IMRT.

Character	VMAT-Hal (Mean±SD)	VMAT-TB (Mean±SD)	H-IMRT (Mean±SD)	VMAT-Hal vs VMAT-TB (p)	VMAT-Hal vs H-IMRT (p)	VMAT-TB vs H-IMRT (p)
Mu	1936.4 ± 424.9	2046.3 ± 472.29	1948.6 ± 237.24	0.96	0.720	0.80
Min	2.42 ± 0.53	3.41 ± 0.79	3.24 ± 0.40	**0.005**	**0.005**	0.80

Discussion

BBC is further classified into synchronous bilateral breast cancer (SBBC) and metachronous bilateral breast cancer (MBBC). BBC diagnosed simultaneously or within a short time interval are considered synchronous, while those diagnosed beyond a certain interval are classified as metachronous [3]. The interval period is typically 3 months [3,5]. BBC is more commonly observed in lobular carcinoma pathology types and multicentric lesions [2]. The prognosis of BBC is similar to that of unilateral breast cancer [2]. MBBC has better prognosis than SBBC [3,5]. Breast-conserving surgery and mastectomy are both commonly used treatment methods for BBC [2]. This study focused on SBBC patients, as this group requires simultaneous bilateral breast/chest wall irradiation. We retrospectively analyzed ten consecutive BBC patients treated with radiotherapy at our center over 5 years, accounting for 1% of all breast cancer radiotherapy cases during the same period. High-risk factors for BBC include young age, family history and genetic mutations. The standardized incidence ratio (SIR) for contralateral breast cancer was 11.4 when diagnosed before age 35, declining to 1.5 after age 60 [6]. Patients with a family history of breast cancer face a 3-fold increased risk of developing contralateral breast cancer [7]. BRCA gene mutation carries an approximately 36% risk of developing contralateral breast cancer within 15 years [8], while CHEK2 gene mutation increases the risk of contralateral breast cancer by 6.5-fold [9]. Approximately 13% of BBC patients have BRCA gene mutations [10]. According to a report from the Mayo Clinic in the United States, 41% of BBC patients underwent genetic testing. Among those tested, pathogenic variants in a breast cancer predisposition gene were present in 23 % patients [2]. In our study, only one patient underwent genetic testing, suggesting more attention should be paid to the application and explanation on genetic testing for BBC patients. The diagnostic rate of BBC is related to the imaging modalities employed, with MRI use increasing the detection rate of BBC [2,11]. In our study, only 1 out of 10 patients underwent MRI examination, suggesting that in future clinical practice, high-risk patients could be considered for MRI scans to facilitate early detection of potential contralateral breast cancer.

This study employed a moderate hypofractionation regimen (40.05Gy/15 fractions). When compared to conventional fractionation (50Gy/25 fractions), acute skin side effects from bilateral irradiation, including dryness, itching, pain and other discomforts can be reduced. Breast tumors have a lower α/β ratio than surrounding normal tissues, and the moderate hypofractionation regimen also helps ensure equivalent tumor biological effective dose (BED) while reducing late side effects [12].

Radiotherapy planning requires complete target coverage (conformity) and dose uniformity (homogeneity). The challenge in BBC radiotherapy planning lies in the doubled irradiation volume and irregular shape. In Hybrid-IMRT planning, beams entering from left and right sides respectively tend to create difficult-to-adjust dose hotspots at the midline, especially when the interval between the left and right PTVs are narrow or the tumor bed happens to be near the inner part of PTV due to the limited adjust field angels and restrict modulation power from the tangential directions. VMAT planning sets the isocenter 2cm below the sternum at the body midline, with wide beam angles (5/6 arcs), providing greater flexibility for dose adjustment and effectively avoiding dose overlap at the midline junction. The advantage of complete and uniform dose coverage for bilateral targets in this study primarily comes from the VMAT design, with no significant differences observed between Halcyon and True beam system.

Only VMAT-Hal plan can fully meet the RTOG 1005 requirements for normal organ sparing, including heart, LAD, lung, liver and skin. The medium doses received by the heart (V20, V30), lung (V30, V40) and Dmean of LAD were significantly lower with the VMAT technique than with the H-IMRT technique. VMAT is more powerful to protect the OARs by adjusting priority values to reduce the maximum dose and scatter dose. The Halcyon system has a lower transmission factor than TrueBeam (Halcyon 0.5% vs TrueBeam 1.5%), a more densely spaced multi-leaf collimator (MLC) leaves (Halcyon 0.01cm, TrueBeam 0.18cm) and less leakage radiation due to its dual-layer MLC design [13], The physical performance advantages of the Halcyon system facilitate further reduction of radiation doses to normal tissues. Therefore, using Halcyon with VMAT technique is more optimal to reduce the acute and late radiation damage, particularly suitable for patients who requires heart dose reduction (e.g. younger patients or those with chemotherapy-induced cardiotoxicity).

The O-ring design of the Halcyon linear accelerator eliminates the risk of patient collision. During treatment, its gantry rotation speed is significantly faster (Halcyon 4 rotations/minute vs. TrueBeam 1 rotation/minute), and its MLC speed is also higher (Halcyon 5 cm/s vs. TrueBeam 2.5cm/s). Additionally, the flattening filter-free (FFF) mode of Halcyon delivers a higher dose rate (Halcyon 800 MU/min vs. TrueBeam 600 MU/min) [14]. Therefore, VMAT-Hal achieves the shortest beam-on time, demonstrating statistically significant differences compared to TrueBeam and Hybrid-IMRT. The faster delivery enhances patient comfort and reduces the impact of intra-fraction motion on treatment accuracy as well. These findings are consistent with similar studies internationally [15-17].

Limitation and Future work

This study is retrospective in nature, with a limited sample size and potential selection bias. Future research should involve larger cohorts and long-term follow-up to validate clinical outcomes. Additionally, further exploration is needed to integrate strategies such as genetic testing, MRI-based assessment as well as personalized radiotherapy planning.

Conclusion

VMAT-Hal achieved better target coverage, superior protection for normal tissues such as the lungs, heart and coronary arteries, and the shortest treatment time. Therefore, Halcyon equipment with VMAT technique can serve as the preferred treatment modality for BBC radiotherapy at our center.

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